Evidence for Superfluidity of Ultracold Fermions in an Optical Lattice

J. K. Chin, D. E. Miller, Y. Liu, C. Stan, W. Setiawan, C. Sanner, K. Xu, W. Ketterle*

Department of Physics, MIT-Harvard Center for Ultracold Atoms,
and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139

The study of superfluid fermion pairs in a periodic potential has important ramifications for understanding superconductivity in crystalline materials. Using cold atomic gases, various condensed matter models can be studied in a highly controllable environment. Weakly repulsive fermions in an optical lattice could undergo d-wave pairing [1] at low temperatures, a possible mechanism for high temperature superconductivity in the cuprates [2]. The lattice potential could also strongly increase the critical temperature for s-wave superfluidity. Recent experimental advances in the bulk include the observation of fermion pair condensates and high-temperature superfluidity [3, 4, 5, 6, 7, 8]. Experiments with fermions [9, 10, 11] and bosonic bound pairs [12, 13] in optical lattices have been reported, but have not yet addressed superfluid behavior. Here we show that when a condensate of fermionic atom pairs was released from an optical lattice, distinct interference peaks appear, implying long range order, a property of a superfluid. Conceptually, this implies that strong s-wave pairing and superfluidity have now been established in a lattice potential, where the transport of atoms occurs by quantum mechanical tunneling and not by simple propagation. These observations were made for unitarity limited interactions on both sides of a Feshbach resonance. For larger lattice depths, the coherence was lost in a reversible manner, possibly due to a superfluid to insulator transition. Such strongly interacting fermions in an optical lattice can be used to study a new class of Hamiltonians with interband and atom-molecule couplings [14].

Previous experiments demonstrating long-range phase coherence in Bose-Einstein condensates (BECs) and in fermion superfluids used ballistic expansion to observe interference of two independent condensates [15], vortex lattices [8, 16, 17] or interference peaks after release from an optical lattice [18, 19]. However, for strongly interacting fermions, elastic collisions can change the momentum distribution and wash out interference peaks. For an initially superfluid cloud, such dissipative dynamics corresponds to superfluid flow faster than the critical velocity. Consistent with this expectation, expansion of the strongly interacting Fermi gas from an optical lattice yielded a diffuse cloud which exhibited no signs of interference (Fig. 1). This issue was addressed by using a magnetic field ramp which quickly increased the detuning from a Feshbach resonance, taking the system out of the strongly interacting regime and enforcing ballistic expansion. In previous studies of strongly interacting Fermi gases magnetic field sweeps were applied to prevent fermion pairs above the Feshbach resonance from dissociating [6, 7, 20]. In contrast, our experiment required a magnetic field sweep both above and below the Feshbach resonance to avoid elastic collisions.

Our experiments used a balanced mixture of ^{6}Li fermions in the two lowest hyperfine states. Evaporative cooling produced a nearly pure fermion pair condensate which was adiabatically loaded into a three-dimensional optical lattice. A broad Feshbach resonance centered at 834 G enabled tuning of the interatomic interactions over a wide range. On resonance, a bound molecular state becomes degenerate with the open atomic

scattering channel, leading to a divergence in the scattering length a. Here we explore the region of strong interactions, also known as the BEC-BCS (Bardeen-Cooper-Schrieffer) crossover, where the magnitude of the interaction parameter $|k_F a|$ is greater than unity, and k_F is defined as the peak Fermi wavevector of a two-component non-interacting mixture of ^{6}Li atoms. Throughout this regime, pairing occurs as a result of many-body interactions. Below resonance, for strong interactions, the bare two-body state has a bond length larger than the interatomic spacing and is irrelevant. In a lattice, atom pairs above and below the resonance can be confined to one lattice site [11], and crossover physics may require an occupation larger than or equal to one.

The peak pair filling factor of the lattice was about unity. At this density in the bulk, the fermion pair size is on the order of $1/k_F = 170$ nm, comparable to the lattice spacing of 532 nm. To probe the momentum distribution, we ramped the magnetic field out of the strongly interacting regime as fast as technically possible (~ 150 μs) and then turned off the confining potential. Absorption images taken after 6.5 ms of expansion reveal sharp peaks at the reciprocal lattice vectors — the signature of long-range coherence and superfluidity.

We observed such interference peaks at magnetic fields both above and below the Feshbach resonance (Fig. 2). The six first order diffracted peaks are clearly visible around the zero momentum fraction and their positions correspond to the expected momentum quanta of $2\hbar k_L$ carried by molecules of mass $2m$, where k_L is the lattice wavevector. At high magnetic fields (Fig. 2d) the visibility of the interference peaks decreased and some additional heating was observed. This degradation could be due to a higher fraction of thermal atoms as we approached the BCS limit, but was not studied in detail.
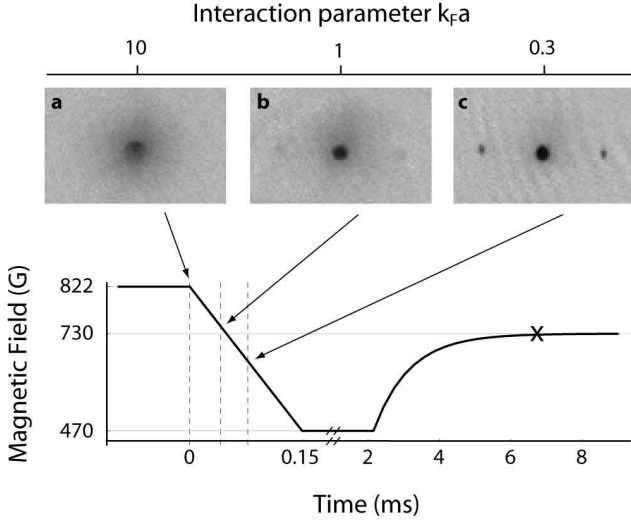
FIG. 1: The schematic shows the time sequence of the magnetic field ramp used throughout this Letter. A one-dimensional optical standing wave was pulsed onto the superfluid at different values B_p (indicated by arrows (**a**) 822 G, (**b**) 749 G and (**c**) 665 G) of the magnetic field during expansion, creating particles at twice the photon recoil [30]. Absorption images taken at the time marked with the cross show distinct momentum peaks only at magnetic fields $B_p \leq 750G$, corresponding to $k_F a \leq 1$. At higher magnetic fields, the peaks blurred into a broad diffuse cloud as a result of the larger collision cross-section.

FIG. 2: (**a**), The orientation of the reciprocal lattice, also with respect to the imaging light. **b-d**, Interference peaks are observed for magnetic fields of (**b**) 822 G, (**c**) 867 G and (**d**) 917 G. The lattice depth for all images is 5 E_r and each image is the average of 3 shots. The field of view is 1 mm by 1 mm. Density profiles through the vertical interference peaks are shown for each image.

The narrow interference peaks clearly reveal the presence of a macroscopic wavefunction possessing long range phase coherence. The separation between the interference peaks relative to their width gives an estimate of the coherence length of ~ 10 lattice sites. This estimate is a lower bound, because effects of finite resolution and mechanisms of residual broadening have been neglected. With unity occupation, and in the absence of any discernible background at magnetic fields near the Feshbach resonance, this implies a minimum phase space density of 10^3, and shows that our samples are deep in the quantum-degenerate regime. In previous studies of ultracold Bose and Fermi gases, the appearance of a condensate fraction and long range phase coherence was shown to occur concurrently with the possibility to excite superfluid flow [8, 16, 17, 21]. Superfluid hydrodynamics is usually regarded as the direct proof for superfluidity. However, all reports of superfluidity of bosons in three-dimensional optical lattices have relied solely on observations of sharp interference peaks and inferred superfluidity from the established connection between long-range coherence and superfluidity [19, 22]. Similarly, our observations directly show long-range coherence and indirectly show superfluidity of fermion pairs in an optical lattice.

For deep lattices, breakdown of superfluid behavior has been observed [19, 23] for weakly interacting Bose-Einstein condensates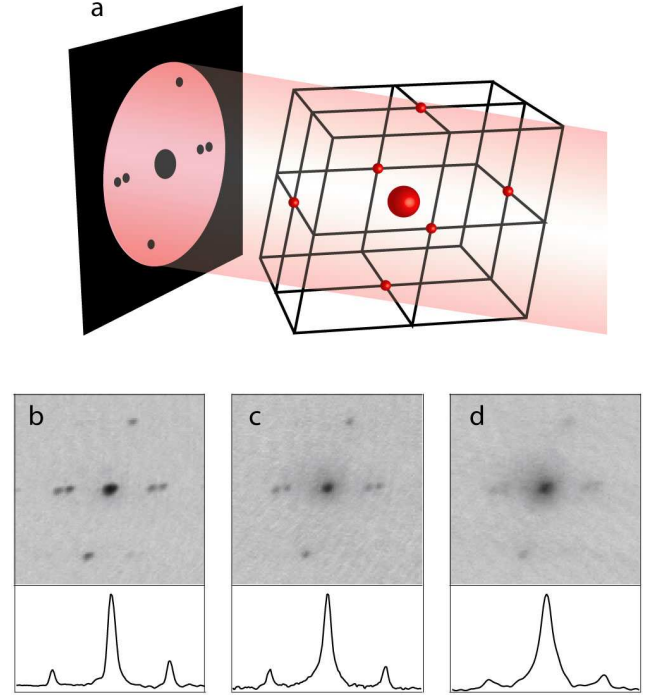. This phase transition to the Mott-insulator state occurs when on-site interactions start to suppress atom number fluctuations and the system transitions from a delocalized superfluid described by a macroscopic wavefunction, to a product of Wannier states tightly localized at each lattice site. Experimentally, this is manifested as a smearing of the distinct $2\hbar k_L$ interference peaks.

Fig. 3 shows the evolution of a strongly interacting fermionic superfluid when the lattice depth was increased. The interference peaks became more pronounced initially, due to increased modulation of the wavefunction. The interference peaks began to smear out, rapidly giving way to a featureless cloud, beyond a critical lattice depth $V_c \approx 6\ E_r$ where $E_r = \hbar^2 k_L^2/4m = h \times$ 15 kHz is the recoil energy. This indicates that all phase coherence had been lost. Upon subsequent ramp down of the lattice, interference peaks became visible again (Fig. 3h), demonstrating reversibility of the lattice ramp.

We repeated this sequence for a wide range of initial magnetic fields both above and below the resonance and observed the same marked change in the interference pattern. Fig. 4 displays the peak optical density of the interference peaks for different lattice depths at representative fields. Across all fields, the sharp decrease in
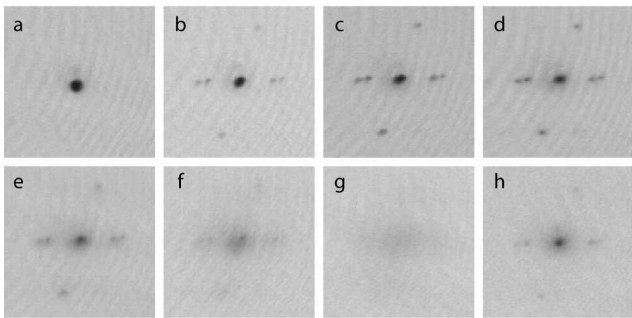
FIG. 3: Values of V_0's are (**a**) 0 E_r , (**b**) 2.5 E_r , (**c**) 4 E_r , (**d**) 5 E_r , (**e**) 6 E_r , (**f**) 7 E_r , (**g**) 9 E_r , (**h**) 2.5 E_r . (**a-g**) were taken after an adiabatic ramp up to the final V_0, while (**h**) was taken after first ramping up to 10 E_r , before ramping down to 2.5 E_r .
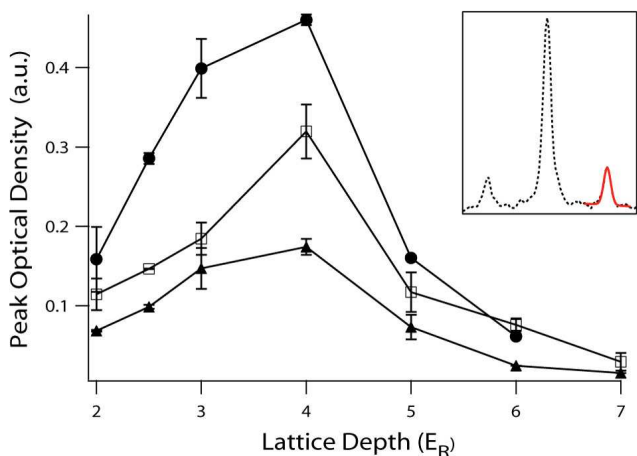

FIG. 4: Values of magnetic fields are 842 G (filled circles), 892 G (open squares) and 942 G (filled triangles). Peak optical densities were estimated from fits to the peaks, including background subtraction. The inset (color online) shows a sample density profile of the central and one pair of interference peaks (black dotted line), with a bimodal fit to one side peak (red solid line). Each point is the average of three different images with six interference peaks per image. Error bars show s. d.

peak optical density occurred between 5 and 6 E_r . Further increase of the magnetic field resulted in decreasing overall visibility, until interference peaks could no longer be observed regardless of lattice depth.

The loss of phase coherence with increasing lattice depth is consistent with the qualitative description of the superfluid to Mott-insulator transition. However, the usual single-band description is no longer applicable, since in the strong-coupling regime the on-site interaction strength should be comparable to the band gap $\hbar\omega$, where ω is the onsite trap frequency. Furthermore, Pauli blocking forbids the multiple occupation of the lowest state of an individual lattice site by identical fermions, and
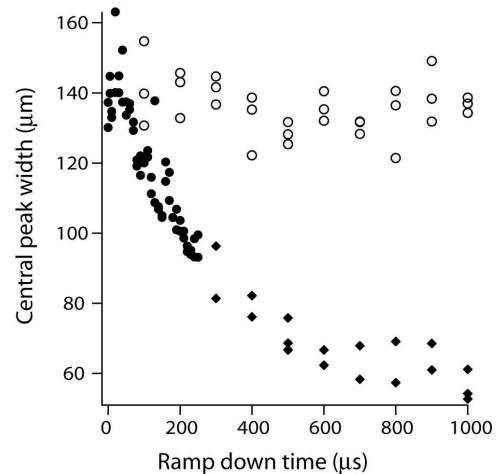

FIG. 5: The width of the central peak is used as a measure of phase coherence after an adiabatic ramp up to 8 E_r followed by a fast ramp down to 2.5 E_r at a fixed magnetic field of 822 G. Filled circles were extracted with the use of a gaussian fit, and diamonds with a bimodal fit. Also plotted for comparison is the gaussian width of the central peak for a dephased sample, in which a field gradient was applied during the ramp up of the lattice (open circles). All points were taken for 6.5 ms time-of-flight.

modification of the single particle tunneling rate is expected due to virtual pair breaking transitions [14]. One may still be tempted to use the standard bosonic Hubbard model and estimate the critical lattice depth V_c for an assumed value of onsite interaction energy $U = \hbar\omega$ and non-interacting, single particle tunneling J, but the obtained $V_c \approx 3$ E_r is significantly smaller than our observation, which is in turn much smaller than the $V_c > 10$ E_r observed for weakly interacting atomic BECs [19, 23]. Along with the observed insensitivity of V_c to magnetic field, this demonstrates that models based on weak interactions are inadequate.

Fig. 3h demonstrates the reversibility of the transition from a long range coherent state to a state without strong coherence. We now study the time scale for this recoherence, in analogy with similar measurements performed across the superfluid to Mott-insulator transition in atomic BECs [19]. Fig. 5 shows that phase coherence was restored on a sub-millisecond time scale, on the order of the the single-particle tunneling time of about 500 μs (for a shallow lattice of 2.5 E_r). When the same lattice ramp sequence was applied to a superfluid which had been dephased by a magnetic field gradient [19] the system did not regain phase coherence on the time scales that we probed. Therefore, evaporative cooling is negligible during this time. The short recoherence time of the condensate is evidence that the system stayed in its ground state or at least in a low entropy state when the lattice was ramped up.

Fig. 5 also provides evidence that the system could not recohere during the 150 μs magnetic field ramp. In

Fig. 3h, the central peak is well fitted by a bimodal distribution with a width of 35 μm, in clear contrast to the gaussian width of 105 μm obtained from Fig. 5 after 150 μs. Therefore, we conclude that the observed interference patterns in Fig. 1 reflect the coherence of the cloud at the initial magnetic field, in the strongly interacting regime.

We have shown long range phase coherence of fermion pairs in an optical lattice in the BEC-BCS crossover region by observing sharp interference peaks during ballistic expansion. This indicates that we have achieved strong s-wave pairing and superfluidity in a lattice potential. Further studies will reveal how the pair wavefunction is affected by confinement [24], and whether the lattice shifts the BEC-BCS crossover away from the Feshbach resonance [25]. The loss of coherence during the lattice ramp up and the rapid recoherence are characteristic of a Mott-insulator. However, definitive proof requires a better understanding of the unitarity-limited interactions in such a Fermi system. Recent theoretical work [14, 26] predicts that strongly interacting fermions in an optical lattice feature multi-band couplings and next-neighbor interactions and can realize the important $t - J$ and magnetic XXZ models of condensed matter theory. This demonstrates that such atomic systems are an ideal laboratory for the exploration of novel condensed-matter physics.

Methods

Clouds of superfluid fermion pairs were created in a new experimental setup [27, 28] using techniques similar to those described elsewhere [8]. In brief, a combination of laser cooling and sympathetic cooling of spin polarized fermions by bosonic ^{23}Na was followed by a spin transfer to create a two component Fermi gas, allowing further cooling via direct evaporation of the fermions. As the fermions cooled, they formed pairs which Bose-condensed.

Estimates of the scattering length and hence the interaction parameter from magnetic field were obtained using $a(B) = -1405a_0(1+300/(B-834))(1+0.0004(B-834))$ [29], where B is measured in Gauss, and a_0 is the Bohr radius. The calibration of the magnetic field in our system had an uncertainty of about 5 G.

Evaporation was performed at a magnetic field of 822 G, where strong interactions allowed for efficient evaporation. An estimated average final number of $N \simeq 2\times10^5$ ^{6}Li pairs and harmonic trapping frequencies of $\nu_{x,y,z} = (270, 340, 200)$ Hz gave a trap depth of 1.7 μK and Fermi energy $E_F = k_B \times 1.4$ μK, where $E_F = \hbar\overline{\omega}(6N)^{1/3}$ and $\overline{\omega}$ is the average trapping frequency. After evaporation, the magnetic field was brought to a desired value B_0 in 20 ms and the condensate allowed to equilibrate for a further 200 ms. Before ramping to values of B_0 on the BCS side, we also recompressed the optical trap to $(340, 440, 270)$ Hz and 2.2 μK depth in 100 ms to accommodate the larger Fermi clouds above the resonance [7].

A three-dimensional optical lattice was formed from three optical standing waves, oriented such that the resulting unit cell has a sheared cubic structure, with one axis tilted ~ 20 degrees from the normal for reasons of optical access (see Fig. 1a) [23]. The incident laser beams were focused down to the condensate with waists of ~ 90 μm, then retro-reflected and overlapped at the condensate to generate the standing wave potentials. All lattice light was derived from a 1064 nm single frequency fiber laser, and each beam was detuned tens of MHz with respect to the others to eliminate interference between different beams.

The lattice potential was imposed onto the condensate by adiabatically increasing the intensity of the laser beams to a variable final value V_0. The calibration of V_0 had an uncertainty of about 20 percent. A simple linear ramp with a constant rate dV_0/dt of 0.5 E_r per ms was used unless otherwise specified. This satisfies the interband adiabaticity condition of $dV_0/dt << 16E_r^2/\hbar$.

Ballistic expansion for the detection of the different momentum components was provided by a magnetic field sequence (shown in Fig. 1) that quickly brought the system out of the strongly interacting regime when all confinement was switched off. During the magnetic field ramp of about 150 μs, the lattice potential was kept on. The first 2 ms of expansion took place at 470 G, where the molecules are tightly bound, before the field was ramped back up to 730 G in the next 4.5 ms, at which the weakly bound molecules strongly absorb light near the atomic resonance line and could be observed by absorption imaging. The specific magnetic field sequence was chosen to minimize collisions within technical capabilities.

[1] Hofstetter, W., Cirac, J. I., Zoller, P., Demler, E. & Lukin, M. D. High-temperature superfluidity of fermionic atoms in optical lattices. *Phys. Rev. Lett.* **89**, 220407 (2002).

[2] Scalapino, D. J. The case for $d_{x^2-y^2}$ pairing in the cuprate superconductors. *Phys. Rep.* **250**, 329–365 (1995).

[3] Greiner, M., Regal, C. A. & Jin, D. S. Emergence of a molecular Bose-Einstein condensate from a Fermi gas. *Nature* **426**, 537 (2003).

[4] Jochim, S. *et al.* Bose-Einstein condensation of molecules. *Science* **302**, 2101 (2003).

[5] Zwierlein, M. W. *et al.* Observation of Bose-Einstein condensation of molecules. *Phys. Rev. Lett.* **91**, 250401

(2003).

[6] Regal, C. A., Greiner, M. & Jin, D. S. Observation of resonance condensation of fermionic atom pairs. *Phys. Rev. Lett.* **92**, 040403 (2004).

[7] Zwierlein, M. W. *et al.* Condensation of pairs of fermionic atoms near a Feshbach resonance. *Phys. Rev. Lett.* **92**, 120403 (2004).

[8] Zwierlein, M. W., Abo-Shaeer, J. R., Schirotzek, A., Schunck, C. H. & Ketterle, W. Vortices and superfluidity in a strongly interacting fermi gas. *Nature* **435**, 1047–1051 (2005).

[9] Modugno, G., Ferlaino, F., Heidemann, R., Roati, G. & Inguscio, M. Production of a Fermi gas of atoms in an optical lattice. *Phys. Rev. A* **68**, 011601(R) (2003).

[10] Köhl, M., Moritz, H., Stöferle, T., Gunther, K. & Esslinger, T. Fermionic atoms in a three dimensional optical lattice: Observing fermi surfaces, dynamics, and interactions. *Phys. Rev. Lett.* **94**, 080403 (2005).

[11] Stöferle, T., Moritz, H., Gunther, K., Köhl, M. & Esslinger, T. Molecules of Fermionic Atoms in an Optical Lattice. *Phys. Rev. Lett.* **96**, 030401 (2006).

[12] Volz, T. *et al.* A Mott state of molecules. *cond-mat/0605184* (2006).

[13] Winkler, K. *et al.* Repulsively bound atom pairs in an optical lattice. *Nature* **441**, 853 (2006).

[14] Duan, L.-M. Effective hamiltonian for fermions in an optical lattice across a feshbach resonance. *Phys. Rev. Lett.* **95**, 243202 (2005).

[15] Andrews, M. R. *et al.* Observation of interference between two Bose condensates. *Science* **275**, 637–641 (1997).

[16] Madison, K. W., Chevy, F., Wohlleben, W. & Dalibard, J. Vortex formation in a stirred Bose-Einstein condensate. *Phys. Rev. Lett.* **84**, 806–809 (2000).

[17] Abo-Shaeer, J. R., Raman, C., Vogels, J. M. & Ketterle, W. Observation of vortex lattices in Bose-Einstein condensates. *Science* **292**, 476–479 (2001).

[18] Anderson, B. P. & Kasevich, M. A. Macroscopic quantum interference from atomic tunnel arrays. *Science* **282**, 1686 (1998).

[19] Greiner, M., Mandel, O., Esslinger, T., Hänsch, T. W. & Bloch, I. Quantum phase transition from a superfluid to a Mott insulator in a gas of ultracold atoms. *Nature* **415**, 39–44 (2002).

[20] Schunck, C.H., Zwierlein, M.W., Schirotzek, A. & Ketterle, W. Superfluid Expansion of a Strongly Interacting Fermi Gas. *cond-mat/0607298* (2006).

[21] Onofrio, R., *et al.* Observation of Superfluid Flow in a Bose-Einstein Condensed Gas. *Phys. Rev. Lett.* **85**, 2228 (2000).

[22] Schori, C. *et al.* Excitations of a Superfluid in a Three-Dimensional Optical Lattice. *Phys. Rev. Lett.* **93**, 240402 (2004).

[23] Xu, K. *et al.* Sodium Bose-Einstein condensates in an optical lattice. *Phys. Rev. A* **72**, 043604 (2005).

[24] Moritz, H. *et al.* Confinement induced molecules in a 1D Fermi gas. *Phys. Rev. Lett.* **94**, 210401 (2005).

[25] Koetsier,A. O.Dickerscheid, D. B. M.,& Stoof,H. T. C. BEC-BCS crossover in an optical lattice. *cond-mat/0604186* (2006).

[26] Gubbels, K. B., Dickerscheid, D. B. M. & Stoof, H. T. C. Dressed molecules in an optical lattice. *cond-mat/0605056* (2006).

[27] Hadzibabic, Z. *et al.* Fifty-fold improvement in the number of quantum degenerate fermionic atoms. *Phys. Rev. Lett.* **91**, 160401 (2003).

[28] Stan, C. A. & Ketterle, W. Multiple species atom source for laser-cooling experiments. *Rev. Sci. Instr.* **76**, 063113 (2005).

[29] Bartenstein, M. *et al.* Precise determination of ^{6}Licold collision parameters by radio-frequency spectroscopy on weakly bound molecules. *Phys. Rev. Lett.* **94**, 103201 (2004).

[30] Gould, P. L., Ruff, G. A. & Pritchard, D. E. Diffraction of atoms by light: the near–resonant Kapitza-Dirac effect. *Phys. Rev. Lett.* **56**, 827 (1986).